STUDY OF GRID CONNECTED INDUCTION GENERATOR FOR WIND POWER APPLICATIONS

a thesis submitted in partial fulfillment of the requirements for a degree of

Bachelor of Technology

in

Electrical Engineering

by

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K. BALA CHAKRI (108EE066)

Department of Electrical Engineering

National Institute of Technology, Rourkela

2012

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Under the guidance of

Prof. K. B. MOHANTY

Department of Electrical Engineering

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National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled ***"STUDY OF GRID CONNECTED INDUCTION GENERATOR FOR WIND POWER APPLICATIONS"*** submitted by Mr. A. Praveen Varma and Mr. K. Bala Chakri in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Electrical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my guidance.

To the best of my knowledge the matter embodied in the thesis has not been submitted to any University/Institute for the award of any Degree or Diploma.

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Date:

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Submitted by:

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CONTENTS

ABSTRACT

Over the past few decades, there has been an increasing use of induction generator particularly in wind power applications. In generator operation, a prime mover (turbine, engine) drives the rotor above the synchronous speed. Stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, active current is produced in stator coils, and motor now operates as a generator, and sends power back to the electrical grid. Based on the source of reactive power induction generators can be classified into two types namely standalone generator and Grid connected induction generator. In case of standalone IGs the magnetizing flux is established by a capacitor bank connected to the machine and in case of grid connection it draws magnetizing current from the grid.

This project explicitly deals with the study of grid connected induction generators where frequency and voltage of the machine will be dictated by the electric grid. Among these types of IGs, Doubly Fed Induction Generator (DFIG) wind turbines are nowadays increasingly used in large wind farms because of their ability to supply power at constant voltage and frequency. Modern control techniques such as Vector control and MFC (magnitude and frequency control) are studied and some of proposed systems are simulated in MATLAB-SIMULINK environment.

FIGURES

LIST OF FIGURES Page No:

NOMENCLATURE

P_{air} Power contained in wind

ρ The air density

A The swept area

V_∞ The wind velocity without rotor interference

C_p Power coefficient

λ Tip speed ratio

ω Rotational speed of rotor

R The radius of the swept area

Vector Control:

d-q Synchronously rotating reference frame direct and quadrature axes

d^s-q^s Stationary reference frame direct and quadrature axes (or a-b axes)

v_{ds}^s d^s-axis stator voltage

v_{qs}^s q^s-axis stator voltage

v_{dr}^s d^s-axis rotor voltage

v_{qr}^s q^s-axis rotor voltage

v_{ds} d-axis stator voltage

v_{qs} q-axis stator voltage

v_{dr} d-axis rotor voltage

v_{qr} q-axis rotor voltage

i_{ds}^s d^s-axis stator current

i_{qs}^s q^s-axis stator current

i_{dr}^s d^s-axis rotor current

i_{qr}^s q^s-axis rotor current

i_{ds} d-axis stator current

i_{qs} q-axis stator current

i_{dr} d-axis rotor current

i_{qr} q-axis rotor current

ψ_{ds}^{s} d^{s}-axis stator flux linkage

ψ_{qs}^{s} q^{s}-axis stator flux linkage

ψ_{dr}^{s} d^{s}-axis rotor flux linkage

ψ_{qr}^{s} q^{s}-axis rotor flux linkage

ψ_{ds} d-axis stator flux linkage

ψ_{qs} q-axis stator flux linkage

ψ_{dr} d-axis rotor flux linkage

ψ_{qr} q-axis rotor flux linkage

θ_{e} Angle of synchronously rotating frame

θ Angle of stationary reference frame

R_{s} Stator resistance

R_{r} Rotor resistance

ω_{e} Synchronous speed

ω_{r} Rotor electrical speed

ω_{m} Rotor mechanical speed

ω_{b} Angular frequency

f Supply frequency

L_{ls} Stator leakage inductance

L_{lr} Rotor leakage inductance

L_{s} Stator inductance

L_{r} Rotor inductance

L_{m} Magnetizing inductance

P Number of poles

T_e	Electromagnetic Torque
T_L	Load torque
J	rotor inertia
B	Damping constant

Synchronised model of DFIG:

$u_{d1}, u_{q1}, u_{d2}, u_{q2}$	2-axis voltages
$i_{d1}, i_{q1}, i_{d2}, i_{q2}$	2-axis currents
$\psi_{d1}, \psi_{q1}, \psi_{d2}, \psi_{q2}$	2-axis flux linkages
L_1, L_2	Machine inductances
L_m	Mutual inductances
r_1, r_2	Machine resistances
ω_1, ω_2	Stator and rotor frequency
ω_r	Rotor speed
U_1, U_2	RMS voltages
I_1, I_2	RMS currents
P_1, P_2	Active Power
Q_1, Q_2	Reactive Power
δ	Power angle
ϕ	Power factor angle
σ	Leakage factor
E_q'	Internal transient EMF
J	Moment of inertia
$\boldsymbol{U_1}, \boldsymbol{U_2}$	Voltage Vectors
$\boldsymbol{I_1}, \boldsymbol{I_2}$	Current vectors
$\boldsymbol{\psi_1}, \boldsymbol{\psi_2}$	Flux linkage vectors
$\boldsymbol{E_q'}$	Internal transient EMF vector

X_1'	Stator transient reactance
X_1	Stator reactance
X_m	Mutual reactance
ψ_2	Rotor flux linkage
T_{em}	Electromagnetic Torque
T_m	Input torque
s	Rotor slip
p	Differential operator
Sub scripts	
d,q	d-q(synchronous axes)
1,2	stator ,rotor

1. WIND ENERGY

1.1 WIND POWER

Wind power is the conversion of wind energy into a suitable form of energy, such as using wind turbines to generate electricity, windmills for mechanical power, wind pumps for water pumping, or sails to propel ships. The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. Wind power, as an alternative to fossil fuels, is abundant, renewable, widely spread, clean, and produces no greenhouse gas emissions during operation. Wind power is the world's rapid growing source of energy.

Why wind energy?

The majority of electricity is generated by burning coal, rather than more eco-friendly methods like hydroelectric power. This use of coal causes untold environmental damage through CO2 and other toxic emissions.

The energy sector is by far the biggest source of these emissions, both in the India and globally, and if we are to tackle climate change it is clear we need to move away from burning limited fossil fuel reserves to more sustainable and renewable sources of energy.

1.2 BENEFITS OF WIND POWER:

Wind power has many advantages that make it a lucrative source of power for both utility-scale and small, distributed power generation applications. The beneficial characteristics of wind power include:

• Clean and endless fuel—Wind power doesn't produce any emissions and is not run down with time. A one megawatt (1 MW) wind turbine for one year can displace over 1,500 tons of carbon dioxide, 6.5 tons of sulphur dioxides, 3.2 tons of nitrogen oxide, and 60 pounds of mercury (based on the U.S. average utility generation fuel mix).

• Local financial development—Wind plants can provide a firm flow of income to landowners who lease their land for wind development, while increasing property tax revenues for local communities.

• Modular and scalable technology—Wind applications can take many forms, including large wind farms, distributed generation, and single end-use systems. Utilities can use wind resources tactically to help reduce load forecasting risks and trapped costs.

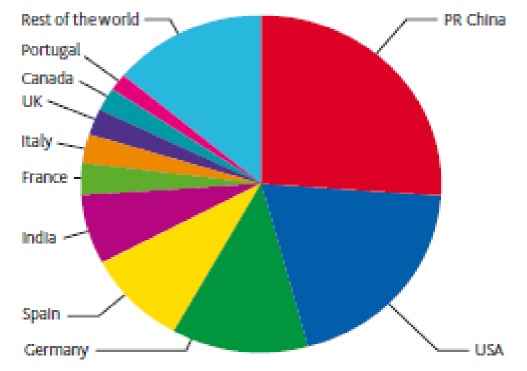
• Energy price stability—by further diversifying the energy mixture, wind energy reduces dependence on conventional fuels that are subject to price and supply instability.

• Reduced dependence on imported fuels—Wind energy expenditures don't need to obtain fuels from abroad, keeping funds closer to home, and lessening reliance on foreign governments that supply these fuels.

1.3 STATISTICS:

With the fast growing demand for power and an emphasis on clean energy, India has also taken its step forward along with other countries. According to the Global Wind Report 2011, the total installed wind capacity at the end of 2011 is just shy of 238 GW. Out of the total capacity India installed wind power generation capacity stood at about 16085MW constitute 6.8% of global wind power capacity.

Top 10 cumulative capacity Dec 2011



Country	MW	% SHARE
PR China	62,364	26.2
USA	46,919	19.7
Germany	29,060	12.2
Spain	21,674	9.1
India	16,084	6.8
France**	6,800	2.9
Italy	6,737	2.8
UK	6,540	2.7
Canada	5,265	2.2
Portugal	4,083	1.7
Rest of the world	32,143	13.5
Total TOP 10	205,526	86.5
World Total	**237,669**	**100.0**

** Provisional Figure — Source: GWEC

Fig: 1.1 Statistical data of Global cumulative wind capacity

WIND ENERGY – INDIAN SCENARIO:

In the early 1980s, the government of India established the Ministry of Non-Conventional Energy Sources (MNES) to promote diversification of the country's energy supply and satisfy the ever-increasing energy demand of its rapidly growing economy. In 2006, this ministry was renamed as the Ministry of New and Renewable Energy (MNRE).

During the first decade of the 21st century, India emerged as the 2nd leading wind power market in Asia. Currently, its cumulative installed capacity is close to 13 GW, with the market growing at an average rate of over 20% over the past 3 years. More than 2,100 MW wind capacity projects were added in the financial year 2010–11. The installed capacity increased from a modest base of 41.3 MW in 1992 to reach 13,065.78 MW by December 2010.

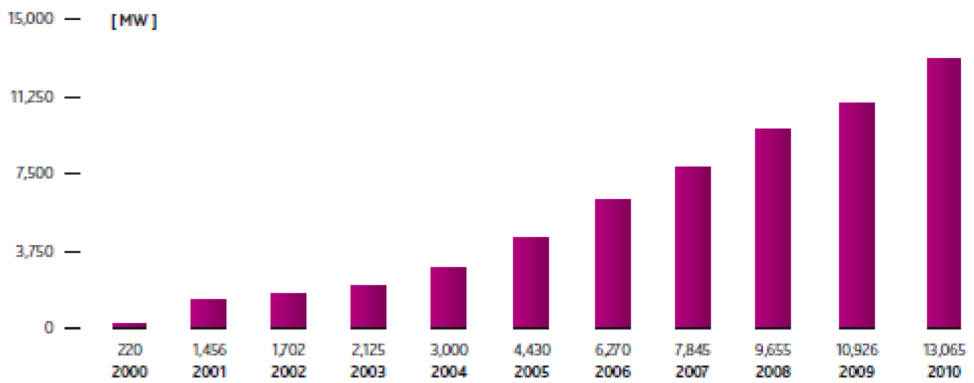


Fig: 1.2 Statistical data of India's wind energy installation

Modern wind power technology has come a long way in the last two decades, both globally and in India. Improved technology has slowly and steadily improved capacity efficiency. A key trend in the Indian industry is the development of multi megawatt turbines installed at greater hub heights. Larger diameter rotors enable a single wind power generator to capture more energy or power per tower. This allows WTGs to take advantage of higher altitudes with stronger winds and less turbulence (wind speed generally increases with height above the ground). Subsequently larger machines have resulted in a steady increase in the capacity factor on average from 10-12% in 1998 to 20-22% in 2010. For two decades now, global average WTG power ratings have grown almost linearly, with present commercial machines rated on average in the range of 1.5 MW to 2.1 MW.

2. WIND ENERGY-GENERATING SYSTEMS

2.1 WIND TURBINES:

Wind turbines produce electricity by using the power of the wind to drive an electrical generator. Passing over the blades, wind generates lift and exerts a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox adjusts the rotational speed to that which is appropriate for the generator, which uses magnetic fields to convert the rotational energy into electrical energy. The power output goes to a transformer, which converts the electricity from the generator at around 700V to the appropriate voltage for the power collection system, typically 33 kV.

A wind turbine extracts kinetic energy from the swept area of the blades. The power contained in the wind is given by the kinetic energy of the flowing air mass per unit time. That is

$$P_{air} = 0.5 \rho A V_{\infty}^{3}$$

Where P_{air} is the power contained in wind (in watts) , ρ is the air density (1.225 kg/m3 at 15°C and normal pressure), A is the swept area in (square meter), and V_{∞} is the wind velocity without rotor interference, i.e., ideally at infinite distance from the rotor (in meter per second).

Although the above equation gives the power available in the wind, the power transferred to the wind turbine rotor is reduced by the power coefficient, C

$$C_P = \frac{P_{Wind\ turbine}}{P_{air}}$$

$$P_{wind\ turbine} = 0.5 \rho C_P A V_{\infty}^{3}$$

Maximum value of C_p is defined by the Betz limit, which states that a turbine can never extract more than 59.3% of the power from an air stream. In reality, wind turbine rotors have maximum Cp values in the range 25-45%.

Solidity: The solidity of a wind rotor is the ratio of the projected blade area to the area of the wind intercepted. The projected blade area is the blade area met by the wind or projected in the direction of the wind.

Solidity has a direct connection with the torque and speed. High-solidity rotors have high torque and low speed, and are employed for pumping water. Low-solidity rotors, on the other hand, have high speed and low-torque, and are usually suited for electrical power generation

TIP SPEED RATIO:

Tip speed ratio of a wind turbine (λ) is defined as:

$$\lambda = \frac{\omega\ R}{V_\infty}$$

Where ω is rotational speed of rotor (in rpm), R is the radius of the swept area (in meter).The tip speed ratio λ and the power coefficient C_p are the dimensionless and so can be used to describe the performance of any size of wind turbine rotor.

SPECIFIED RATED CAPACITY:

Specified Rated capacity (SRC) is an important index which is used to compare a variety of wind turbine designs.

$$SRC = \frac{Power\ Rating\ Of\ The\ Generator}{Rotor\ Swept\ Area}$$

It varies between 0.2 (for small rotors) and 0.6 (large rotors)

2.2 CHARACTERISTICS OF WIND TURBINE:

Various Characteristics of wind turbine are plotted to have a better understanding.

POWER-SPEED CHARACTERISTICS:

Mechanical Power transmitted to the shaft is:

$$P_m = 0.5\rho C_P A V_\infty{}^3$$

Where

C_P is a function of tip speed ratio (TSR) and pitch angle α

For wind turbine with radius

The following curves show the relationship between mechanical power extracted from the wind and the rotor speed at various wind speeds. For each wind speed there is an optimum turbine speed at which maximum power is extracted.

Such a group of wind turbine curves can be represented by a single dimensionless characteristic curve, explicitly, the $C_p - \lambda$ curve as shown in figure2.2

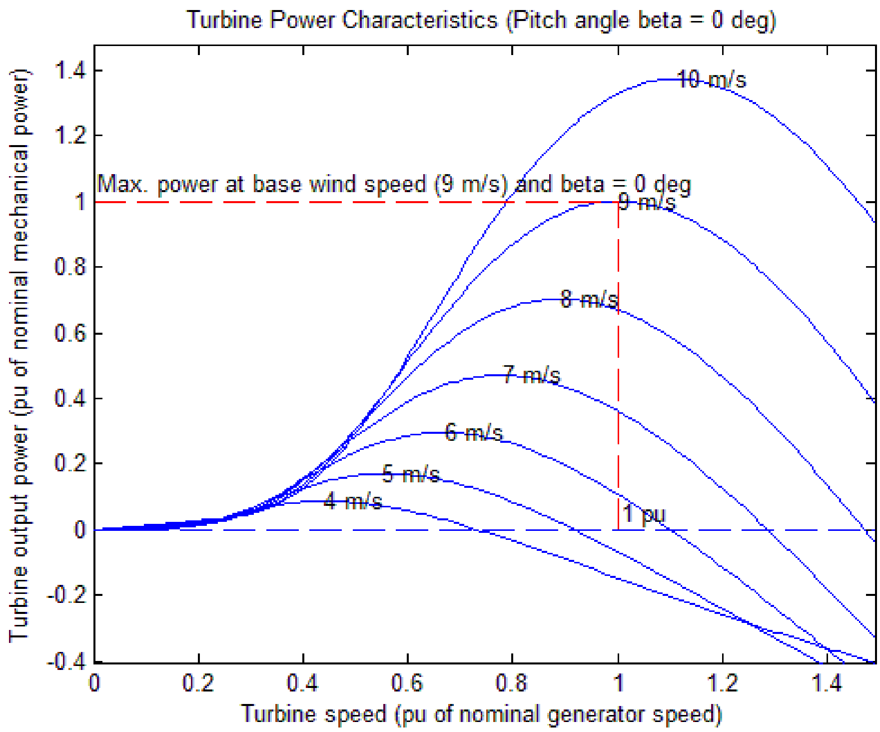


Fig: 2.1 Typical Power versus speed characteristics of a wind turbine

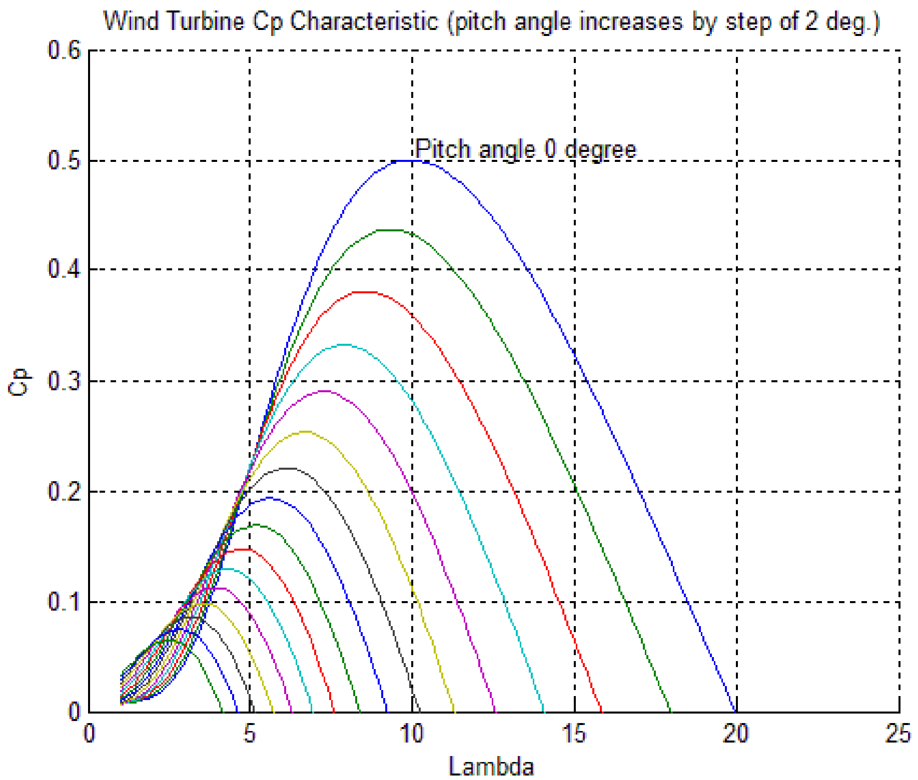


Fig: 2.2 Typical curves of power coefficient (C_P) Versus Tip speed ratio (λ)

for various angles of pitch angle

TORQUE –SPEED CHARACTERISTICS:

The typical torque versus speed characteristics of horizontal axis (two blade propeller type) wind turbine is shown:

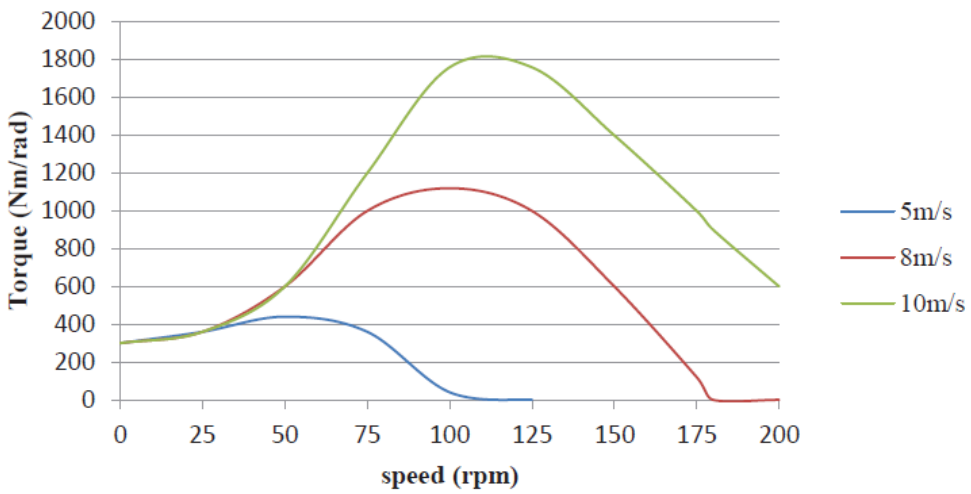


Fig: 2.3 Torque versus speed characteristics

The direct relationship between Torque and Power is:

$$T_m = \frac{P_m}{\omega}$$

Using the optimum values of C_P and λ, the maximum value of aerodynamic torque is:

$$T_{max} = 0.5\rho C_{P-opt}\pi\left(\frac{R^5}{\lambda_{opt}^3}\right)\omega^2$$

The curve shows that for any wind speed the torque reaches peak value at a definite rotational speed, and this maximum torque varies in the order of the square of rotational speed. Generally the load torque depends on the electrical loading. The torque can be made to vary as the square of the rotational speed by choosing the load properly.

Different control techniques such as Pitch angle control, Stall control (active and passive), Power electronic control and Yaw control are used to control the wind turbines.

3. INDUCTION GENERATOR

An induction generator or asynchronous generator is a type of AC electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotor in generator mode, giving negative slip. In most cases, a regular AC asynchronous motor is used as a generator, without any internal modifications.

PRINCIPLE OF OPERATION:

Induction generators and motors produce electrical power when their rotor is rotated faster than the synchronous frequency. For a typical four-pole motor (two pairs of poles on stator) operating on a 60 Hz electrical grid, synchronous speed is 1800 rotations per minute. Similar four-pole motor operating on a 50 Hz grid will have synchronous speed equal to 1500 rpm. In normal motor operation, stator flux rotation is faster than the rotor rotation. This is initiating stator flux to induce rotor currents, which create rotor flux with magnetic polarity opposite to stator. In this way, rotor is dragged along behind stator flux, by value equal to slip. In generator operation, a prime mover (turbine, engine) drives the rotor above the synchronous speed. Stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, active current is produced in stator coils, and motor is now operating as a generator, and sending power back to the electrical grid.

Grid and stand-alone connections:

In induction generators the magnetizing flux is established by a capacitor bank connected to the machine in case of stand-alone system and in case of grid connection it draws magnetizing current from the grid.

- For a grid connected system, frequency and voltage of the machine will be dictated by the electric grid, since it is very small compared to the whole system.
- For stand-alone systems, frequency and voltage are complex function of machine parameters, capacitance used for excitation, and load value and type.

3.1 GRID CONNECTED INDUCTION GENERATOR

Grid connected induction generators develop their excitation from the Utility grid. The generated power is fed to the supply system when the IG is run above synchronous speed. Machines with cage type rotor feed only through the stator and generally operate at low negative slip. But wound rotor machines can feed power through the stator as well as rotor to the bus over a wide range known as Doubly Fed Induction Machines [2].

FIXED SPEED GRID CONNECTED WIND TURBINE GENERATOR:

The structure and performance of fixed-speed wind turbines as shown in Fig. 3.1 depends on the features of mechanical sub-circuits, e.g., pitch control time constants etc.

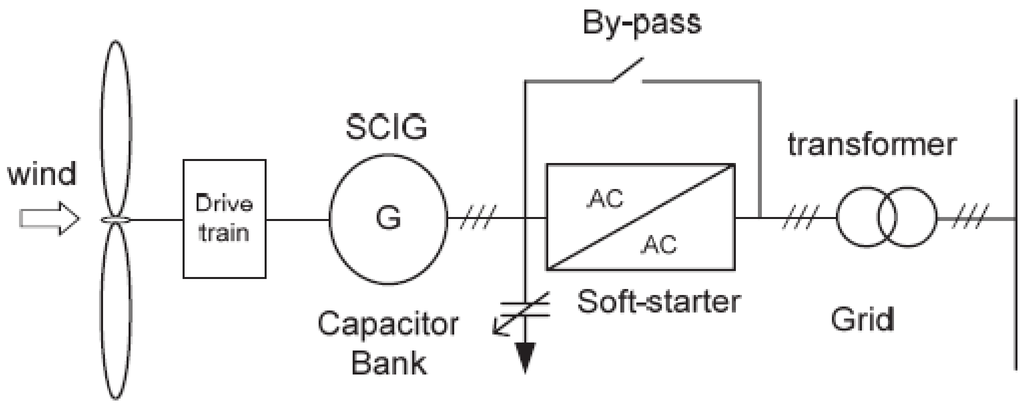


Fig 3.1: fixed speed wind turbine with directly grid connected squirrel-cage induction generator

The reaction time of these mechanical circuits may lie in the range of tens of milliseconds. As a result, each time a burst of wind hits the turbine, a rapid variation of electrical output power can be observed. These variations in electric power generated not only require a firm power grid to enable stable operation, but also require a well-built mechanical design to absorb high mechanical stress, which leads to expensive mechanical structure, especially at high-rated power.

Variable Speed Wind Turbine Generator:

A way to make more convenient turbines is variable speed turbines. Variable speed turbines have become the most dominating type of the yearly installed wind turbines as they can store some of the power fluctuations due to turbulence by increasing the rotor speed, pitching the rotor blades, these turbines can control the power output at any given wind speed.

Fig. 3.2 shows a variable speed turbine connected to a Squirrel- Cage Induction Generator SCIG. Although these direct-online systems have been built up to 1.5 MW, but presence of power inverter causes lots of disadvantages such as:

a) This power converter, which has to be rated at 1 p.u. of total system power, is expensive.
b) Converter efficiency plays an important role in total system efficiency over the entire operating range.

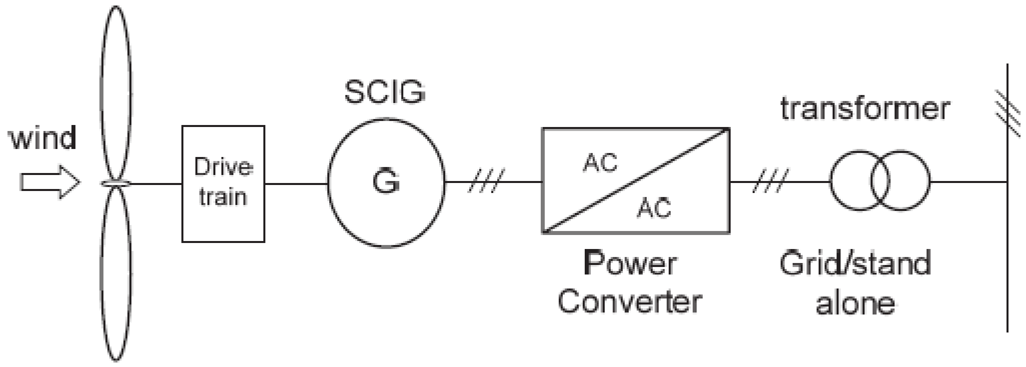


Fig 3.2: variable speed wind turbine with squirrel-cage induction generator

Another way is using Doubly Fed Induction Generator DFIG, as shown in Fig.3.3 It consists of a stator connected directly to grid and a rotor – via slip rings – is connected to grid through four-quadrant ac-to-ac converter based on insulated gate bipolar transistors (IGBTs)
This system offers the following advantages:

1. Reduced inverter cost, because inverter rating is typically 30% of total system power.
2. Improved system efficiency.
3. Power-factor control can be implemented at lower cost.
4. It has a complete control of active and reactive power.

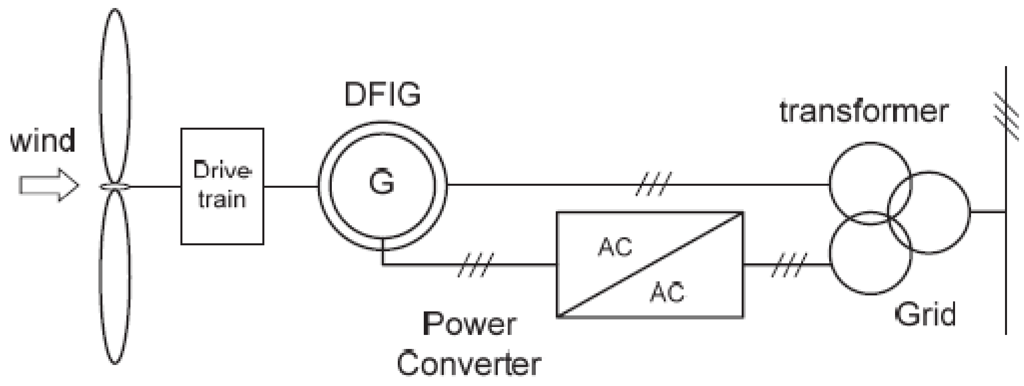


Fig 3.3: Variable speed wind turbine with doubly-fed induction generator

The doubly fed induction generator with a power converter shown in Fig. 3.3 is a simple and highly controllable way to transform the mechanical energy from the variable speed rotor to a constant frequency electrical utility grid. The main reason for the popularity of the doubly fed wind induction generators connected to the national networks is their ability to supply power at constant voltage and frequency while the rotor speed varies.

4. DOUBLY FED INDUCTION GENERATOR

Currently DFIG wind turbines are increasingly used in large wind farms. A typical DFIG system is shown in the below figure. The AC/DC/AC converter consists of two components: the rotor side converter C_{rotor} and Grid side converter C_{grid} .These converters are voltage source converters that use forced commutation power electronic devices (IGBTS) to synthesize AC voltage from DC voltage source. A capacitor connected on DC side acts as a DC voltage source. The generator slip rings are connected to the rotor side converter, which shares a DC link with the grid side converter in a so called back -to-back configuration. The wind power captured by the turbine is converted into electric power by the IG and is transferred to grid by stator and rotor windings. The control system gives the pitch angle command and the voltage commands for C_{rotor} and C_{grid} to control the power of the wind turbine, DC bus voltage and reactive power or voltage at grid terminals.

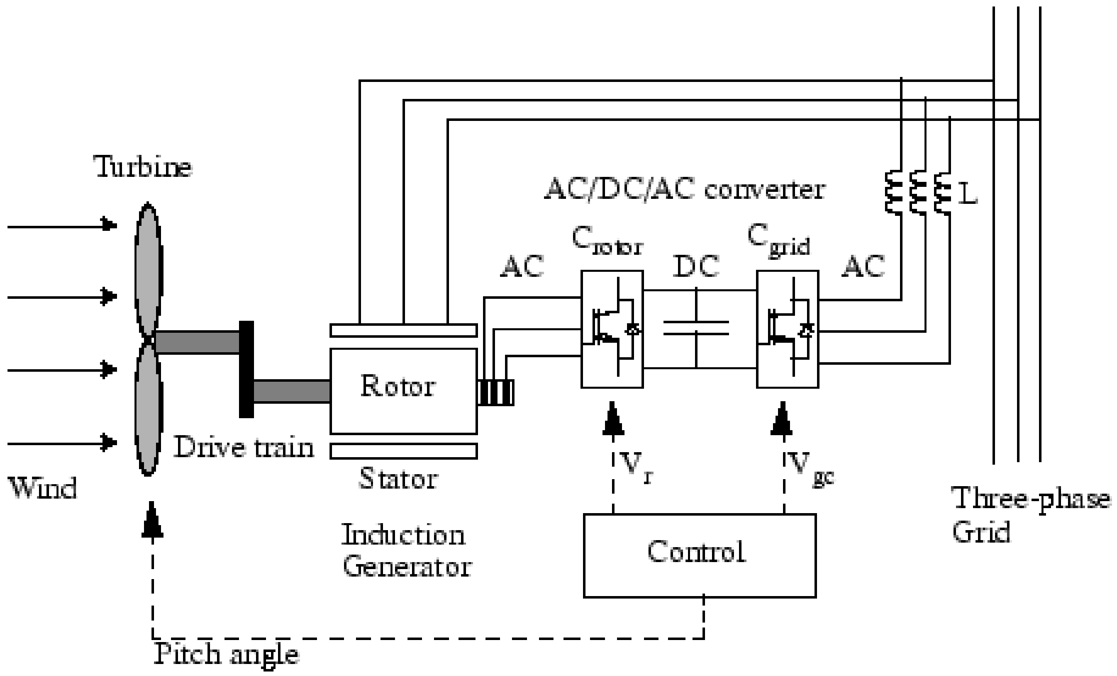


Fig4.1 : A DFIG and wind turbine system

OPERATION:

When the rotor speed is greater than the rotating magnetic field from stator, the stator induces a strong current in the rotor. The faster the rotor rotates, the more power will be transferred as an electromagnetic force to the stator, and in turn converted to electricity which is fed to the electric grid. The speed of asynchronous generator will vary with the rotational force applied to it. Its difference from synchronous speed in percent is called generator's slip. With rotor winding short circuited, the generator at full load is only a few percent.

With the DFIG, slip control is provided by the rotor and grid side converters. At high rotor speeds, the slip power is recovered and delivered to the grid, resulting in high overall system efficiency. If the rotor speed range is limited, the ratings of the frequency converters will be small compared with the generator rating, which helps in reducing converter losses and the system cost.

Since the mechanical torque applied to the rotor is positive for power generation and since the rotational speed of the magnetic flux in the air gap of the generator is positive and constant for a constant frequency grid voltage, the sign of the rotor electric power output is a function of the slip sign. C_{rotor} and C_{grid} have the capability of generating or absorbing reactive power and can be used for controlling the reactive power or the grid terminal voltage. The pitch angle is controlled to limit the generator output power to its normal value for high wind speeds. The grid provides the necessary reactive power to the generator.

4.1 Steady state characteristics:

The steady state performance can be explained using Steinmetz per phase equivalent circuit model as shown in figure where motor convention is used. In this figure v_s and v_r are the stator and rotor voltages, i_s and i_r are the stator and rotor currents, r_s and r_r are the stator and rotor resistances (per phase), X_s and X_r are stator and rotor leakage reactance's, X_m is the magnetizing reactance and *s* is slip.

The steady state equivalent circuit of DFIG is shown in Fig.4.2

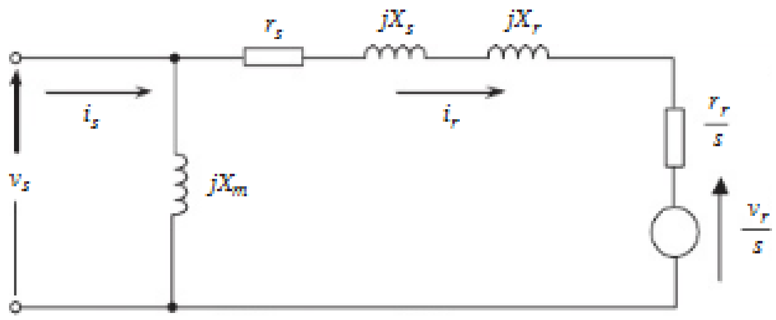


Fig: 4.2 steady state equivalent circuit of DFIG

To obtain the torque equation from the equivalent circuit, we can simplify the steady state induction motor circuit by moving X_m to the stator terminal .The rotor current I_r is expressed as

$$I_r = \frac{V_s - \left(\frac{V_r}{s}\right)}{\left(r_s + \frac{r_r}{s}\right) + j(X_s + X_r)}$$

The electrical torque T_e, from the power balance across the stator to rotor gap, can be calculated from

$$T_e = \left(I_r{}^2 \frac{r_r}{s}\right) + \frac{P_r}{s}$$

Where the power supplied or absorbed by the controllable source injecting voltage into the rotor circuit, that is the rotor active power, P_r can be calculated from

$$P_r = \frac{V_r}{s} I_r \cos\theta$$

$$P_r = Re\left(\frac{V_r}{s} I^*{}_r\right)$$

TORQUE-SLIP CHARACTERISTICS OF DFIG:

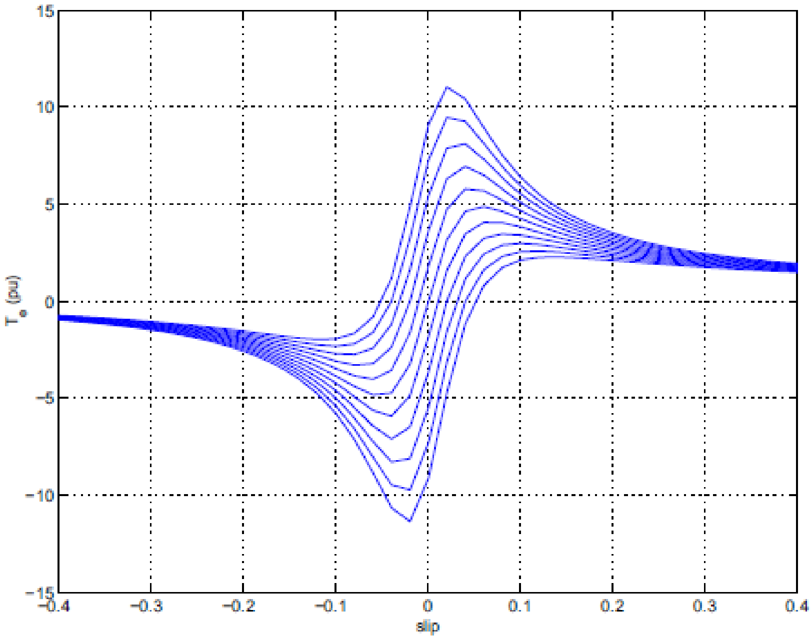


Fig: 4.3Torque-slip characteristic when the angle of Vr is 0.

|Vr| is changing from -0.05 to +0.05 pu.

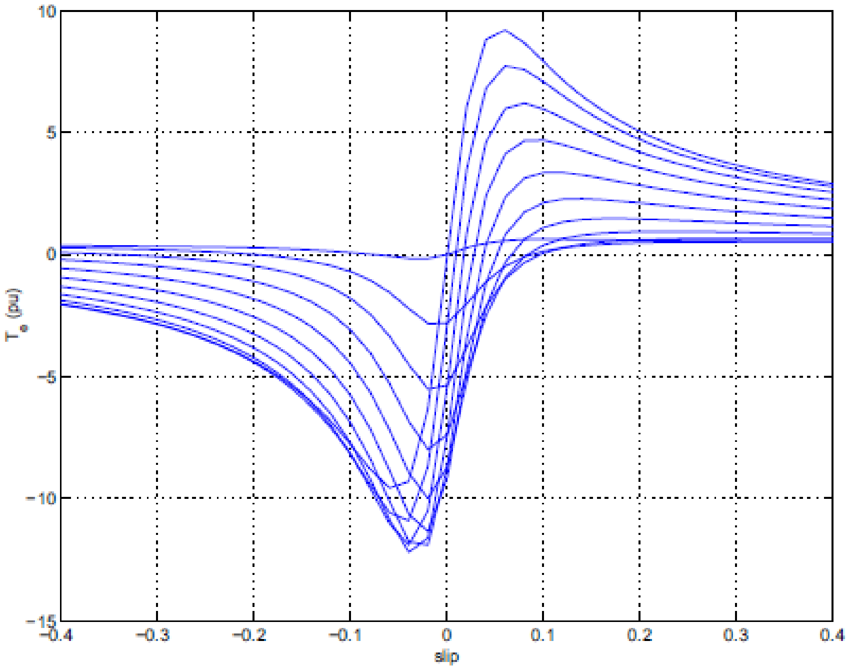


Fig: 4.4Torque-slip characteristic when |Vr| is 0.05 pu.

The angle of Vr is changing from −90◦ to +90◦.

4.2 CONTROL STRATEGIES FOR A DFIG:

1. Vector control
2. Magnitude and frequency control

4.2.1 VECTOR OR FIELD ORIENTED CONTROL THEORY:

The complete control strategy of the machine is divided in two ways, one is scalar control and the other is vector control. The limitations of scalar control give a significance to vector control. Though the scalar control strategy is modest to implement but the natural coupling effect gives sluggish response. The inherent problem is being solved by the vector control. The vector control is invented in the beginning of 1970s. Using this control strategy an IM can be performed like dc machine. Because of dc machine like performance vector control is also known as orthogonal, decoupling or Tran's vector control. Different Vector control strategies have been proposed to control the active and reactive power of an induction generator.

The basic of the vector control theory is d-q theory. To understand vector control theory knowledge about d-q theory is essential.

D-Q THEORY:

The d-q theory is also known as reference frame theory. The history says in 1920, R. H. Park suggested a new theory to overcome the problem of time varying parameters with the ac machines. He formulated a change of variables which replace the variables related to the stator windings of a synchronous machine with variables related with fictitious winding which rotates with the rotor at synchronous speed.

Essentially he transformed the stator variables to a synchronously rotating reference frame fixed in the rotor. With such transformation (Park's transformation) he showed that all the time varying inductances that occur due to an electric circuit in relative motion and electric circuit with varying magnetic reluctances can be eliminated. Later in 1930s H. C. Stanley showed that time varying parameters can be eliminated by transforming the rotor variables to the variables associated with fictitious stationary windings.

In this case the rotor variables are transformed to the stationary reference frame fixed on the stator. Later G. Kron proposed transformation of stator and rotor variables to a synchronously rotating reference frame which moves with rotating magnetic field. Latter, Krause and Thomas had shown that the time varying Inductances can be eliminated by referring the stator and rotor variables to an arbitrary reference frame which may rotate at any speed [5].

TRANSFORMATION OF THREE PHASE STATIONARY TO TWO PHASE STATIONARY AXES:

Consider a symmetrical three phase induction machine with stationary a-phase, b phase and c-phase axes are placed at 120° angle to each other as shown in Fig 4.5. The main aim is to transform the three phase stationary frame variables into two phase stationary frame variables (d^s-q^s) and then transform these to synchronously rotating reference frame variables (d-q), and vice versa.

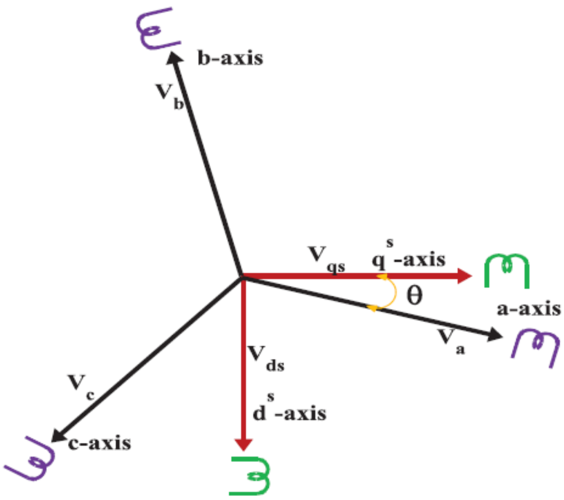


Fig 4.5: Transformation of a-b-c to d^s-q^s axes

Let d^s-q^s axes are oriented at an angle θ from a-b-c axes as shown in Fig 4.2 The voltage ($V_{ds}{}^s$ and $V_{qs}{}^s$) can be resolved into a-b-c components and can be represented in the matrix form as

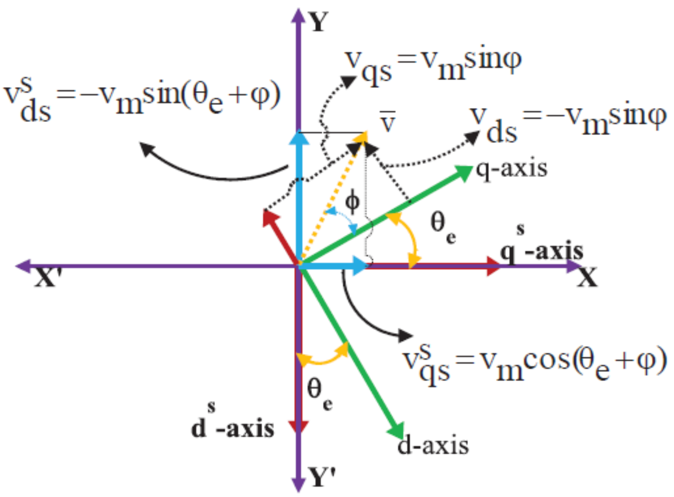
$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-120°) & \sin(\theta-120°) & 1 \\ \cos(\theta+120°) & \sin(\theta+120°) & 1 \end{bmatrix} \begin{bmatrix} v^s{}_{qs} \\ v^s{}_{ds} \\ v^s{}_{0s} \end{bmatrix} \qquad (4.1)$$

The corresponding inverse relation is

$$\begin{bmatrix} v^s{}_{qs} \\ v^s{}_{ds} \\ v^s{}_{0s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-120°) & \cos(\theta+120°) \\ \sin\theta & \sin(\theta-120°) & \sin(\theta+120°) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (4.2)$$

Where $v^s{}_{0s}$ is added as the zero sequence component. Other parameters like current, flux linkages can be transformed by similar manner. It is more convenient to set θ=0°, so that q-axis is aligned with the a-axis in this case (The alignment of the axes are optional, d-axis can also be aligned with a-axis). The sine components of d and q parameters will be replaced with cosine values, and vice versa if d-axis coincides with a-axis.

Transformation of two phase stationary axes to two phase synchronously rotating axes:



4.6 Transformation of stationary d^s-q^s axes to synchronously rotating frame d-q axes

Fig 4.6 above shows the synchronously rotating d-q axes which rotate at synchronous speed ω_e with respect to d^s-q^s axes. The two phase windings are transformed in to the fictitious windings mounted on the d-q axes.

The voltages on the d^s-q^s axes can be converted into d-q axes as follows;

$$v_{qs} = v^s{}_{qs}\cos\theta_e - v^s{}_{ds}\sin\theta_e \quad (4.3)$$

$$v_{ds} = v^s{}_{qs}\sin\theta_e + v^s{}_{ds}\cos\theta_e \quad (4.4)$$

Again resolving the rotating frame parameters into a stationary frame the relations are

$$\mathrm{v^s}_{\mathrm{qs}} = \mathrm{v}_{qs}\cos\theta_e + \mathrm{v}_{ds}\sin\theta_e \qquad (4.5)$$

$$\mathrm{v^s}_{\mathrm{ds}} = -\mathrm{v}_{qs}\sin\theta_e + \mathrm{v}_{ds}\cos\theta_e \qquad (4.6)$$

Mathematical modelling of Induction Generator:

In this section the basic mathematical modelling of DFIG is described in detail. From the previous section we confirm that the three phase parameters can be represented in two phase parameters and vice versa using certain fundamental rules. In this section the machine modelling is explained by taking two phase parameters into consideration. Though the basic concepts behind the DFIG system is explained briefly in short we can say the DFIG is a wound rotor type induction machine, its stator consists of stator frame, stator core, poly phase (3-phase) distributed winding, two end covers, bearing etc. The stator core is made up of stack of cylindrical steel laminations which are slotted along their inner periphery for covering the 3-phase winding. Its rotor consists of slots in the outer periphery to house the windings like stator. The machine works on the principle of Electromagnetic Induction and the energy transfer takes place by means of transfer action. So the machine can represent as a transformer but rotatory not stationary.

Modelling of DFIG in synchronously rotating frame:

The equivalent circuit diagram of an induction machine is shown in Fig.4.7 and Fig.4.8. In this figure the machine is represented as two phase machine, it has already been discussed before that a three phase machine can be represented as two phase machine obeying certain rules. For the modelling of DFIG in synchronously rotating frame we need to represent the two phase stator (d^s-q^s) and rotor (d^r-q^r) circuit variables in a synchronously rotating (d-q) frame.

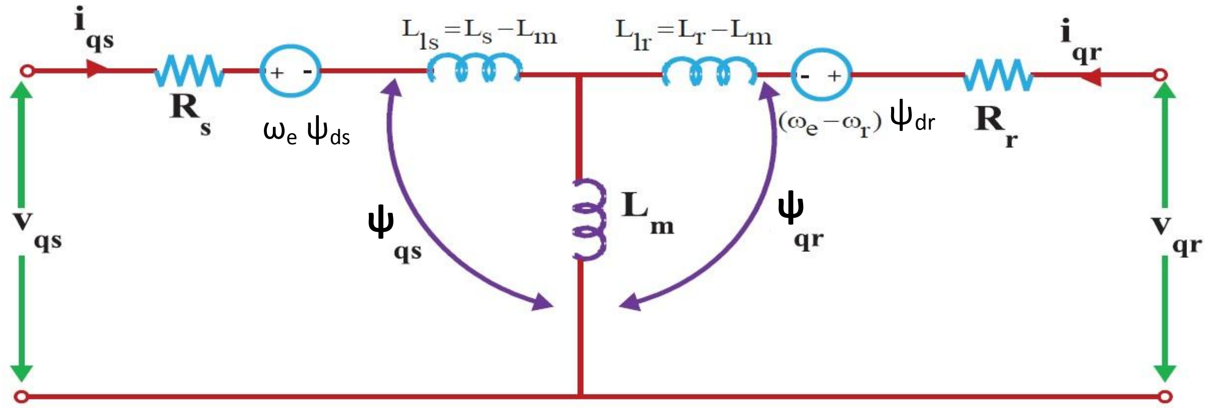


Fig.4.7 Dynamic d-q equivalent circuit of DFIG (q-axis circuit)

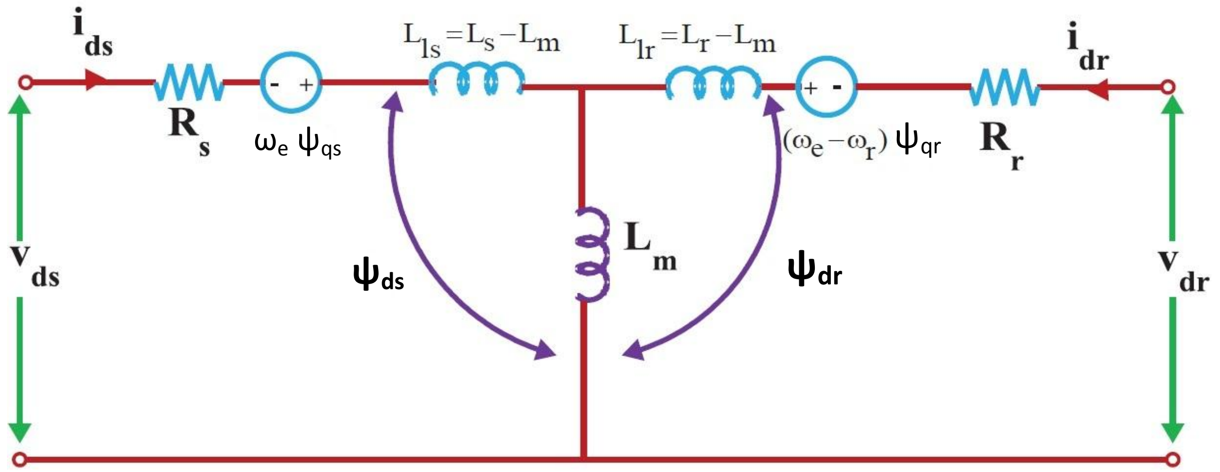


Fig.4.8 Dynamic d-q equivalent circuit of DFIG (d-axis circuit)

The stator circuit equations are given below:

$$v^s{}_{qs} = R_s i^s{}_{qs} + \frac{d}{dt}\psi^s{}_{qs} \qquad (4.7)$$

$$v^s{}_{ds} = R_s i^s{}_{ds} + \frac{d}{dt}\psi^s{}_{ds} \qquad (4.8)$$

Where $\psi^s{}_{qs}$ and $\psi^s{}_{ds}$ are q-axis and d-axis stator flux linkages, respectively. Converting Eq. (4.7) and Eq. (4.8) to d-q frame the following equations can be written as:

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e \psi_{ds} \qquad (4.9)$$

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e \psi_{qs} \qquad (4.10)$$

Where all the variables are in synchronously rotating frame. The bracketed terms are defined as the back e.m.f. or speed e.m.f or counter e.m.f. due to the rotation of axes as in the case of

DC machines. When the angular speed ω_e is zero the speed e.m.f due to d and q axis is zero and the equations changes to stationary form.

Owing to the rotor circuit, if the rotor is blocked or not moving, i.e. ω_r=0, the machine equations can be written in similar way as stator equations:

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \omega_e \psi_{dr} \tag{4.11}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_e \psi_{qr} \tag{4.12}$$

All the parameters are referred to the primary circuit, which is a stator in this case. Let the rotor rotates at an angular speed ω_r, then the d-q axes fixed on the rotor fictitiously will move at a relative speed ω_e-ω_r to the synchronously rotating frame.

The d-q frame rotor equations can be written by replacing ω_e-ω_r in place ω_e of as follows:

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \tag{4.13}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \tag{4.14}$$

The flux linkage expressions in terms of current can be written from Fig.4.7 and Fig.4.8 as follows:

$$\psi_{qs} = L_{ls} i_{qs} + L_m(i_{qs} + i_{qr}) = L_s i_{qs} + L_m i_{qr} \tag{4.15}$$

$$\psi_{ds} = L_{ls} i_{ds} + L_m(i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr} \tag{4.16}$$

$$\psi_{qr} = L_{lr} i_{qr} + L_m(i_{qs} + i_{qr}) = L_r i_{qr} + L_m i_{qs} \tag{4.17}$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m(i_{ds} + i_{dr}) = L_r i_{dr} + L_m i_{ds} \tag{4.18}$$

$$\psi_{qm} = L_m(i_{qs} + i_{qr}) \tag{4.19}$$

$$\psi_{dm} = L_m(i_{ds} + i_{dr}) \tag{4.20}$$

Eq. (4.7) to Eq. (4.20) describes the complete electrical modelling of DFIG. Whereas the Eq. (4.21) expresses the relations of mechanical parameters which are essential part of the modelling.

The electrical speed ω_r cannot be treated as constant in the above equations. It can be connected to the torque as

$$T_e = T_L + J\frac{d\omega_m}{dt} + B\omega_m = T_L + \frac{2}{p}J\frac{d\omega_r}{dt} + \frac{2}{p}B\omega_r \qquad (4.21)$$

PRINCIPLE OF VECTOR CONTROL:

The fundamentals of implementation of vector control technique can be explained using the Fig 4.9 In this figure the machine model is in synchronously rotating frame. The vector control uses unit vectors to obtain the appropriate control action. The main role of unit vector is to convert the 2-phase model to 3-phase model and vice versa. Though the control techniques used for DFIG uses two axes parameters as explained in the modelling via vector control but the model is virtual representation of the original machine. The control signals which will be fed to the original machine or converters should be in three axes form, so the process requires repeated conversion of two-phase to three-phase parameter or vice versa following the necessary action being taken for the system [6]. There are essentially two general method of vector control

- Direct or feedback method (which is invented by Blaschke)
- Indirect or feed forward method (which is invented by Hasse)

The two methods are different from each other by the process of generating unit vector for control. Unit vectors ($\cos\theta_e$, $\sin\theta_e$) are generally generated using the flux vectors, but it can also be generated using voltage vectors. The name of the orientation of unit vector is given according to the vector taken for generation of θ_e. The names of the orientations used are given below.

- Rotor flux orientation
- Stator flux orientation
- Air gap flux orientation

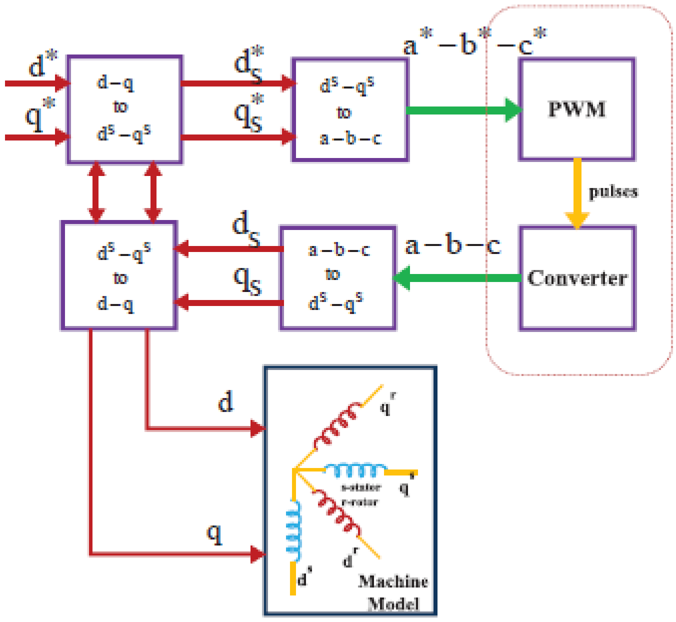


Fig 4.9 Implementation of vector control principle

The detail vector control strategy is shown in above figure. The a, b, c components are generated from the controlled components a*, b*, c* respectively using vector control techniques. The machine terminal parameters (either voltages or currents) are converted to d^s-q^s components by 3-phase to 2-phase transformation. These are then converted to synchronously rotating frame by the unit vector before applying to the 2-phase machine model. The controller makes two stage of inverse transformation as shown, so that the control components d* and q* corresponds to the machine parameters d and q respectively.

4.2.2 SYNCHRONISED MODEL OF GRID CONNECTED DOUBLY FED INDUCTION GENERATOR FOR WIND POWER GENERATION:

MAGNITUDE AND FREQUENCY CONTROL OF DFIG:

A magnitude and frequency control (MFC) strategy has been proposed for the grid connected doubly fed induction generator (DFIG).The proposed MFC makes the DFIG equivalent to a synchronous generator in the power system .The active and reactive powers of the stator depend on the phase and magnitude of the new equivalent ‘emf behind the internal transient reactance’. The relationship between the rotor voltage and the ‘emf behind the internal transient reactance’ is also detailed. Unlike traditional control strategies such as stator-flux-orientation vector control and FMAC, the MFC method manipulates the magnitude and frequency of the rotor voltage. This simplifies the design of the control system and improves system reliability. Thus, co-ordinate transformations, rotor position detection, and measurements of rotor currents and rotor speeds are not required [3].

SYNCHRONISED MODEL OF DFIG:

MODELLING OF DFIG STATOR:

It is assumed that the stator transient can be neglected in this paper. The effects of neglecting stator transients in DFIG model were analysed. Besides analysis, includes simulated waveforms which establish that the stator transients in DFIG can be neglected and the accuracy is not affected after the transients have damped out.

By neglecting the stator transient, the voltage equations of the DFIG in the arbitrary d-q reference frame can be expressed as follows (stator in generator convention and rotor in motor convention)

$$u_{d1} = -r_1 i_{d1} - \psi_{q1}\omega_1$$
$$u_{q1} = -r_1 i_{q1} - \psi_{d1}\omega_1$$
$$u_{d2} = -r_2 i_{d2} + p\psi_{d2} - \psi_{q2}\omega_2$$
$$u_{q2} = -r_2 i_{q2} + p\psi_{q2} - \psi_{d2}\omega_2$$

The corresponding flux linkage equations:

$$\psi_{d1} = -L_1 i_{d1} - L_m i_{d2}$$
$$\psi_{q1} = -L_1 i_{q1} + L_m i_{q2}$$
$$\psi_{d2} = L_2 i_{d2} - L_m i_{d1}$$
$$\psi_{q2} = L_2 i_{q2} - L_m i_{q1}$$

Setting the d-axis to align with the rotor flux vector, one defines $\psi_2 = \psi_{d2}$. A consequence of the rotor flux alignment is $\psi_{q2} = 0$.

Thus, rotor currents can be expressed in terms of stator currents as:

$$i_{d2} = \frac{\psi_2 + L_m i_{d1}}{L_2}$$

$$i_{q2} = \frac{L_m}{L_2 i_{q1}}$$

In order to eliminate the rotor variables in stator equations, define

$$E'_q = \omega_1 \frac{L_m}{L_2} \psi_2$$

$$X'_1 = \sigma\omega_1 L_1$$

Where E'_q is the equivalent 'emf behind the internal transient reactance' which is generated by the rotor flux linkage ψ_2, X'_1 is the transient reactance of the stator, and
$\sigma = (L_1L_2 - L^2_m)/ L_1L_2$ is the leakage factor.

By substituting, the stator voltage equations can be written as follows:

$$u_{d1} = -r_1 i_{d1} + X'_1 i_{q1}$$

$$u_{q1} = -r_1 i_{q1} - X'_1 i_{d1} + E'_q$$

Neglecting the stator resistance, the vector diagram of the DFIG stator can be drawn as shown in Fig 4.7 according to above equations.
In this vector diagram, δ is the power angle between the vector $\boldsymbol{E'_q}$ and $\boldsymbol{U_1}$ and ϕ is the phase angle between the vector $\boldsymbol{U_1}$ and $\boldsymbol{I_1}$. Based on Fig 4.7, the stator currents can be calculated as

$$i_{d1} = \frac{E'_q - U_1 \cos\delta}{X'_1}$$

$$i_{q1} = \frac{U_1 \sin\delta}{X'_1}$$

Then the equations of active and reactive powers of the DFIG stator:

$$P_1 = U_1 I_1 \cos\phi = \frac{E'_q U_1}{X'_1} \sin\delta$$

$$Q_1 = U_1 I_1 \sin\phi = \frac{E'_q U_1}{X'_1} \cos\delta - \frac{{U_1}^2}{X'_1}$$

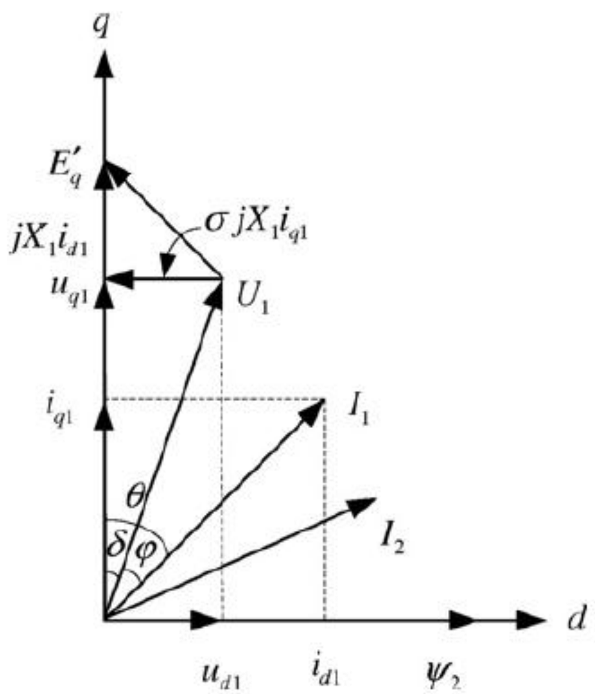


Fig 4.10: Vector diagram of the DFIG

It can be seen that the DFIG has the same expression of active and reactive powers as the synchronous machine. Developing from and adding the stator resistance r1, Fig: 4.11 is the single line equivalent circuit of the DFIG. It is similar to that of the synchronous generator except the excitation voltage is different, because it is controlled from a more complex rotor equivalent circuit.

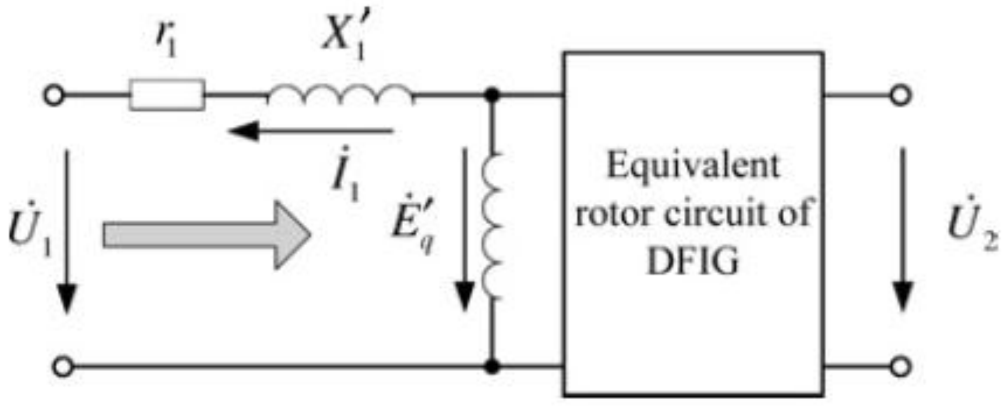


Fig 4.11: Equivalent circuit of DFIG

The power angle in synchronous generator is relatively small in normal operation which is often below 30 degrees. This condition can be also met in DFIG. With this condition the classic synchronous generator theory indicates that the active power transfer depends mainly on the power angle and the reactive power transfer depends mainly on the voltage magnitude of $\boldsymbol{E'_q}$, respectively. By similarity of synchronous generator, the control of the stator active power and reactive power of the DFIG can be seen as the control of phase and magnitude of $\boldsymbol{E'_q}$. The DFIG has a benefit in that the power angle δ (and therefore the active power) is controllable by the rotor converter whereas δ in the synchronous generator is determined by the axis of the field winding.

4.4.2 MODELLING OF THE DFIG ROTOR:

By substituting rotor flux equations into the rotor voltage equations, the rotor voltages can be expressed as:

$$u_{d2} = r_2 \frac{\psi_2}{L_2} + r_2 \frac{L_m}{L_2} + p\psi_2$$

$$u_{q2} = r_2 \frac{L_m}{L_2} i_{q1} + \psi_2 \omega_2$$

Equation above can be re-expressed in the vector form as follows:

$$\boldsymbol{U_2} = r_2 \frac{L_m}{L_2} \boldsymbol{I_1}_{+} \left(\frac{r_2 + \omega_2 L_2 + p}{\omega_1 L_m} \right) \boldsymbol{E'_q}$$

Replacing the stator current vector with $I_1 = (E'_q - U_1) / X'_1$, becomes

$$\boldsymbol{U_2} = \left(\frac{r_2 L_m}{\sigma L_2 X_1} + \frac{r_2}{X_m} + \frac{\omega_2 L_2}{X_m} + p \right) \boldsymbol{E'_q} - \frac{r_2 L_m}{\sigma L_2 X_1} \boldsymbol{U_1}$$

Equation above describes the relationship between the stator voltage vector $\boldsymbol{U_1}$, the rotor voltage vector $\boldsymbol{U_2}$ and the internal transient EMF vector $\boldsymbol{E'_q}$. The stator voltage $\boldsymbol{U_1}$ is the same as the grid voltage and thus $\boldsymbol{E'_q}$ can be controlled by U_2.

Unlike the exciter of the synchronous generator which can only adjust the magnitude of the exciter voltage only, the rotor controller of the DFIG can manipulate both the magnitude and the phase angle of $\boldsymbol{U_2}$ vector. Thus, the active and reactive powers of the DFIG can be controlled by $\boldsymbol{U_2}$ vector.

MODELLING THE DFIG-BASED WIND TURBINE:

The active power of the DFIG rotor can be expressed as:

$$P_2 = u_{d2} i_{d2} + u_{q2} i_{q2}$$

From the above equations, the active power of the rotor can be expressed as:

$$P_2 = P_{r2} + \frac{\omega_2}{\omega_1} P_1$$

Where,

$$P_{r2} = r_2 i_{d2}^2 + r_2 i_{q2}^2$$

is the power losses associated with the rotor resistance, which is small enough to be ignored. It can be shown that the active power of the rotor depends on the rotor current frequency, stator frequency and the active power of the stator. Depending on the rotor speed ω_r, the rotor current frequency, $\omega_2 = \omega_1 - \omega_r$, can be positive and negative and therefore the rotor power changes direction. The active power of the rotor is positive when the DFIG operates at the sub-synchronous mode ($\omega_1 > \omega_r$) and negative when the DFIG operates at the super-synchronous mode ($\omega_1 < \omega_r$). The grid-side converter, in maintaining the DC-link voltage regulated, feeds or absorbs the slip dependent rotor active power. The reactive power of the grid side converter is set to zero to give a unity displacement factor.

MECHANICAL EQUATION OF MOTION:

The stator voltage vector $\boldsymbol{U_1}$ rotates at the speed of ω_1 of the grid frequency. The rotating speed of $\boldsymbol{E'_q}$ is the algebraic sum two speeds: the rotor speed ω_r and the rotor current angular frequency ω_2. So the equation of the power angle is:

$$\dot{\delta} = (\omega_r + \omega_2) - \omega_1$$

The equation of motion of the rotor is:

$$J\dot{\omega}_r = T_m - T_{em}$$

Where T_m is the input torque from the wind turbine and T_{em} is the electromagnetic torque of the DFIG.

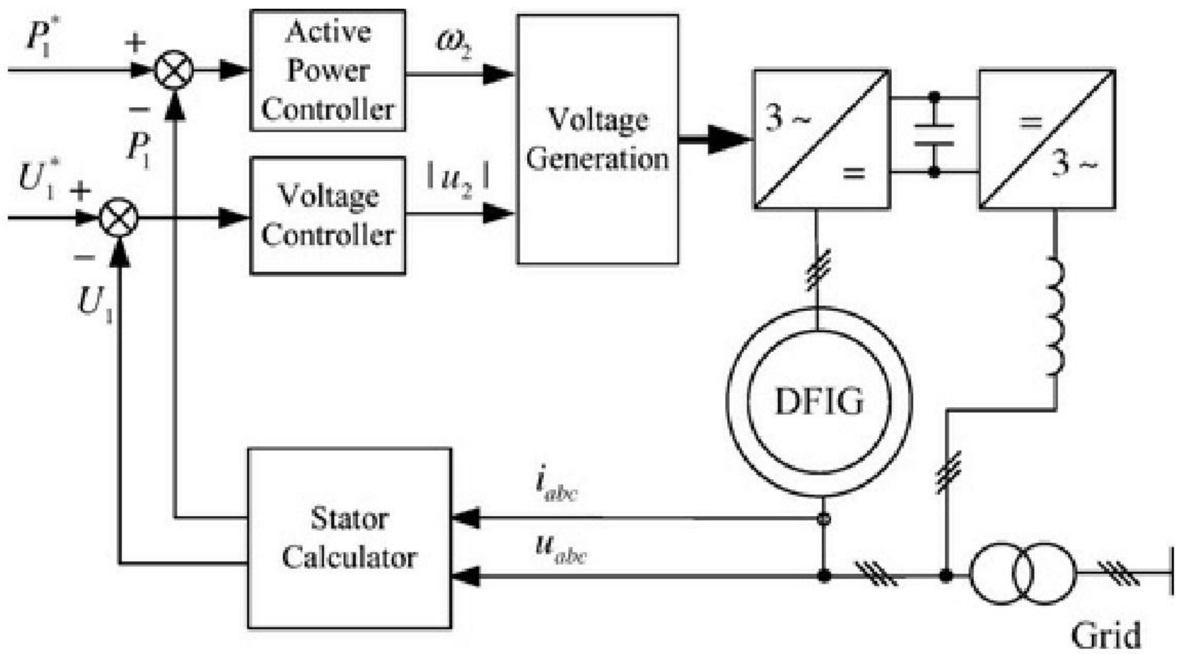


Fig: 4.12 MFC Controller Diagram

5. SIMULATIONS

5.1 PITCH CONTROL ANALYSIS BY MATLAB:

Explanation:

$$P_m = 0.5C_p(\lambda,\beta)\rho A V_w^3$$

Where

P_m is mechanical output power of the wind turbine;

$C_p(\lambda,\beta)$ is the performance coefficient of the turbine;

ρ is the density of air in kg/m^3;

A is the swept area of turbine;

V_w is the wind speed (m/s);

λ is the tip speed ratio;

β pitch angle of blade in degrees;

A basic equation used to model $C_p(\lambda,\beta)$:

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda} - c_3\beta - c_4\right)e^{\frac{c_5}{\lambda_i}} + c_6\lambda$$

and

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

The coefficients c1 to c6 are: c1 = 0.5176, c2 = 116, c3 = 0.4, c4 = 5, c5 = 21 and c6 = 0.0068. The Cp-λ characteristics, for different values of the pitch angle β, are illustrated below. The maximum value of Cp (Cpmax = 0.48) is achieved for β = 0 degree and for λ = 8.1. This particular value of λ is defined as the Nominal value (λ_nom).

PROGRAM:

```
L=0.01:0.1:15;
c1=0.5176;
c2=116;
c3=0.4;
c4=5;
c5=21;
c6=0.0068;
pitch=0:5:25;
for i=1:6
    for p=1:length(L);
        A(p)=1/(L(p)+0.08*pitch(i))-0.035/(pitch(i)^3+1);
        C(p)=c1*(c2*A(p)-c3*pitch(i)-c4)*exp(-c5*A(p))+c6*L(p);
    end
    plot(A(p),C(p));
    hold on;
end
axis ([0 15 -0.1 0.5]);
xlabel('\lambda'),ylabel('Cp');
```

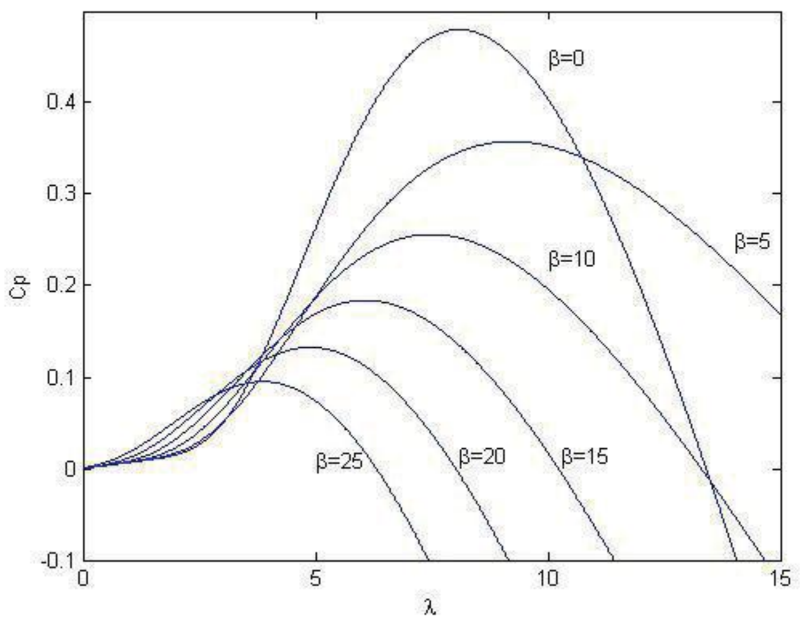


Fig: 5.1 Power coefficients versus tip speed ratio

5.2 MECHANICAL CHARACTERISTICS ANALYSIS BY MATLAB

PROGRAM:

% mechanical_characteristics.m

% numerical simulations of the power coefficient of the wind turbine as a function of the tip

% speed rate and the pitch angle.

```
c1=0.5176; c2=116; c3=0.4; c4=5; c5=21; c6=0.0068; r0=1.29;
D=40; A=pi*D^2/4;
L=0.01:0.1:15;
b=0;
V=[8,10,12,14,16,18,20];
for k=1:length(V)
    for p=1:length(L);
        AI(p)=1/(L(p))-0.035;
        CP(p)=c1*(c2*AI(p)-c4)*exp(-c5*AI(p))+c6*L(p);
        P(k,p)=(V(k)^3)*CP(p)*r0*A/2;
        n(k,p)=(60/(pi*D))*AI(p)*V(k);
    end;
    hold on;
end;
M=max(P(6,:)); m=max(M); P=P/m; n1=length(L); n2=length(V);
for j=1:n1;
    P(:,n1-j+1)=P(:,j);
end;
PR=P;
for q=1:n2;
    plot(n(q,:), PR(q,:)); hold on
end;
grid; axis([0.1,1.45,-0.1,1.4]);
xlabel('rotational speed(relative units)'),ylabel('power
(relative units)');
```

RESULT:

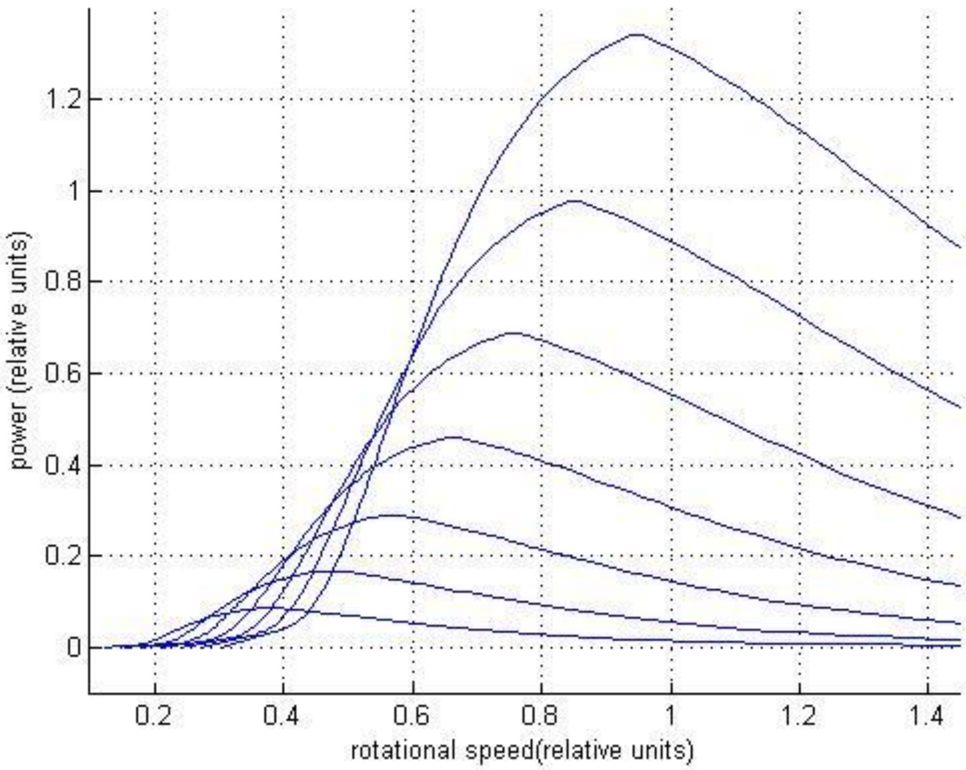


Fig: 5.2 Wind turbine output power vs. rotational speed, with wind speed as parameter

5.3 TORQUE-SLIP CHARACTERISTICS

Torque-slip characteristic when the angle of V_r is 0. $|V_r|$ is changing from -0.05 to +0.05 pu:

MATLAB code:

```
Xls=0.0135;
Xlr=0.0075;
rs=0.00059;
rr=0.00339;
Vs=0.5;
Vr=-0.05:0.01:0.05;
for i=1:11
    s=-1:0.01:1;
    for j=1:201
        T(i,j)=(s(j)*Vs^2-
Vs*Vr(i))*(s(j)*rs+rr)/((s(j)*rs+rr)^2+s(j)^2*(Xls+Xlr)^2);
    end;
    plot(s,T);
end;
axis([-1,1,-15,15])
xlabel('slip'),ylabel('Torque (pu)');
```

RESULT:

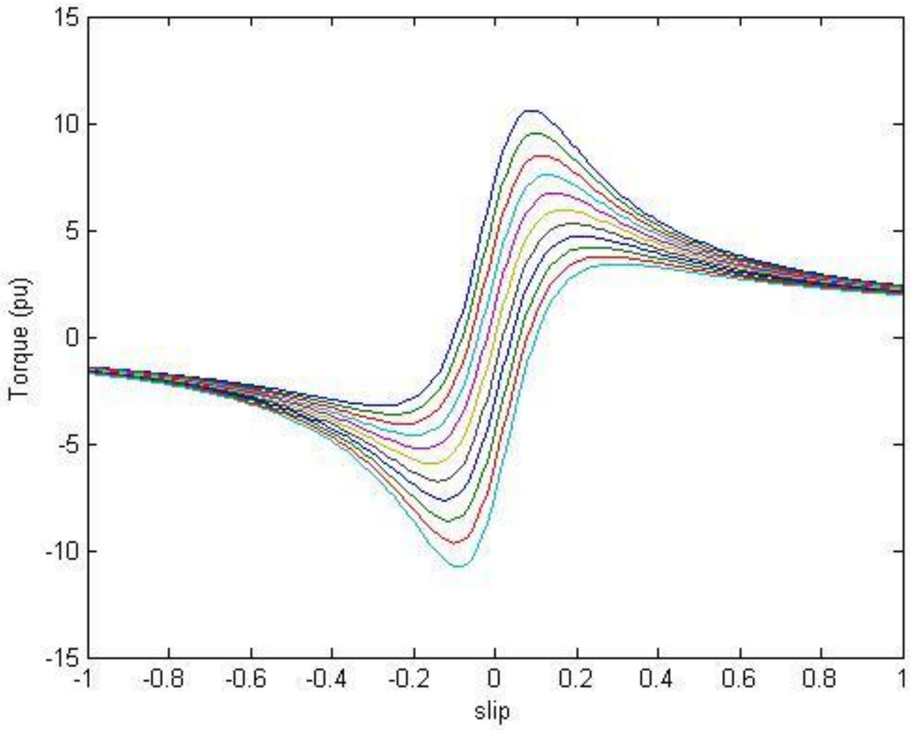


Fig: 5.3 Torque-slip characteristic when the angle of Vr is 0. |Vr| is changing from -0.05 to +0.05 pu.

TORQUE-SLIP CHARACTERISTIC WHEN |V_r| IS 0.05 pu. THE ANGLE OF V_r IS CHANGING FROM -90° TO+90°

MATLAB code:

```
clc;
clear all;
Xls=0.0135;
Xlr=0.0075;
rs=0.00059;
rr=0.00339;
Vs=0.5;
Vr=0.05;
angle_deg=-90:20:90;
angle_rad=deg2rad(angle_deg);
for i=1:length(angle_deg)
    s=-1:0.01:1;
    for j=1:201
        T(i,j)=(((s(j)*Vs^2-
Vs*Vr*cos(angle_rad(i)))*(s(j)*rs+rr))+(Vs*Vr*s(j)*(Xls+Xlr)*s
in(angle_rad(i))))/((s(j)*rs+rr)^2+s(j)^2*(Xls+Xlr)^2);
    end;
    plot(s,T);
end;
% axis([-1,1,-15,15])
xlabel('slip'),ylabel('Torque(pu)');
```

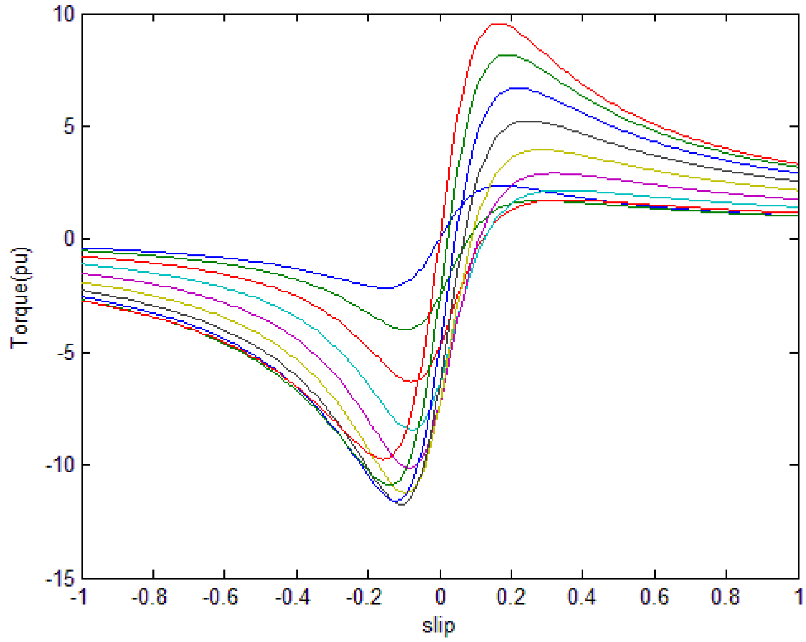


Fig: 5.4 Torque-slip characteristic when |Vr| is 0.05 pu. The angle of Vr is changing from -90° to +90°

5.3 STUDY OF WTDFIG IN A 9MW WIND FARM CONNECTED TO A 25KV, 60 HZ SYSTEM

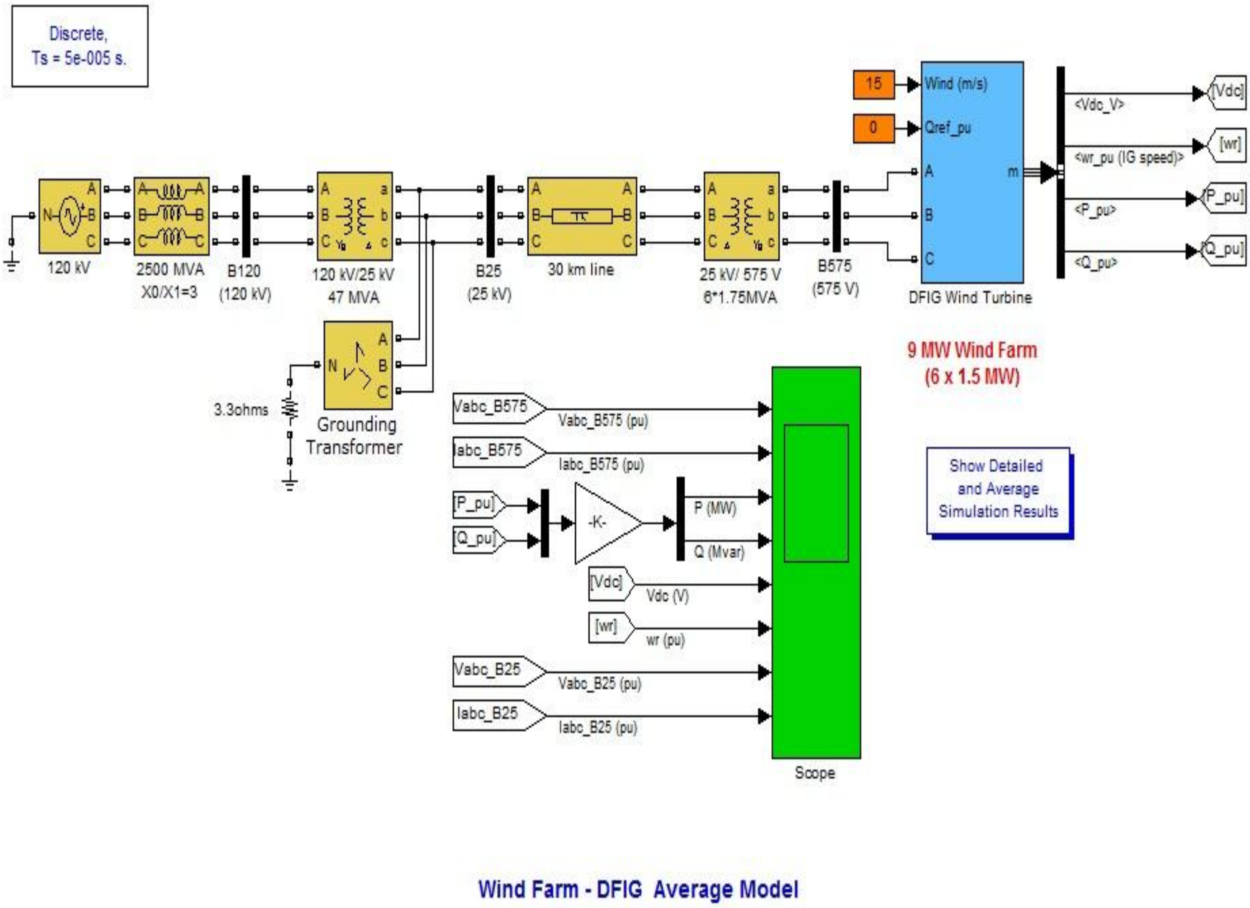


Fig: 5.5 Wind farm DFIG Average Model

SIMULATION RESULTS OF DFIG AVERAGE MODEL

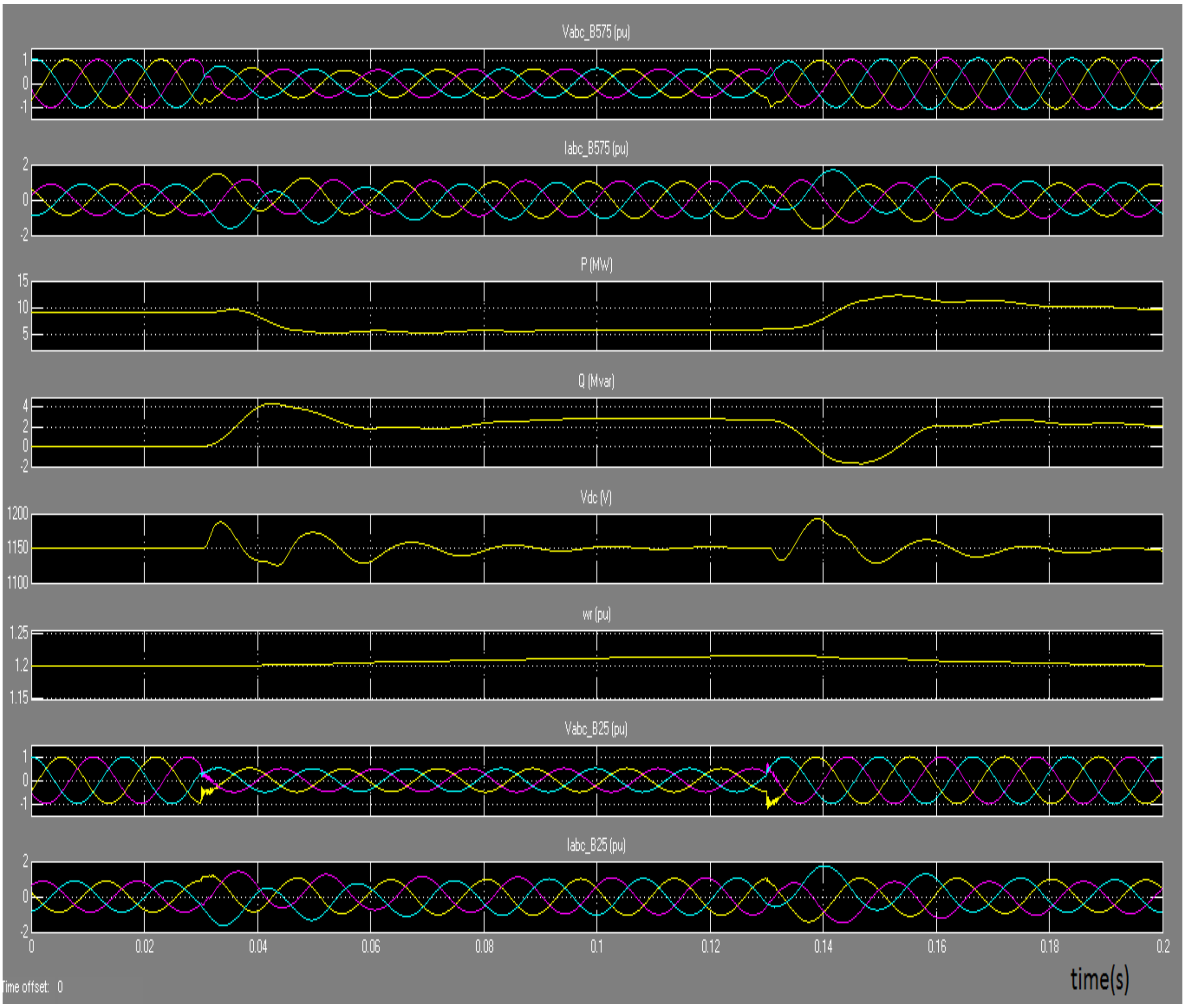


Fig: 5.6 Simulation results of DFIG average model

5.4 SIMULINK MODEL FOR MAGNITUDE AND FREQUENCY CONTROL OF DFIG:

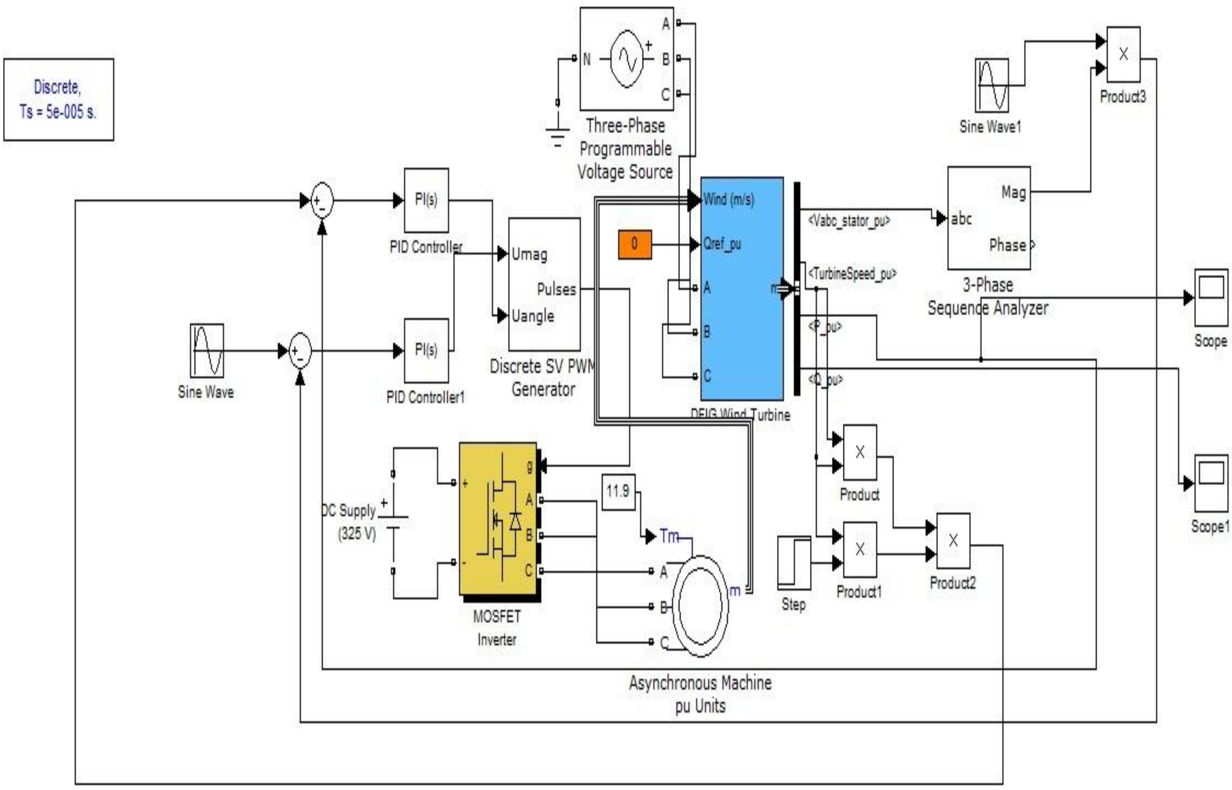


Fig: 5.7 Simulink model for MFC

RESULTS

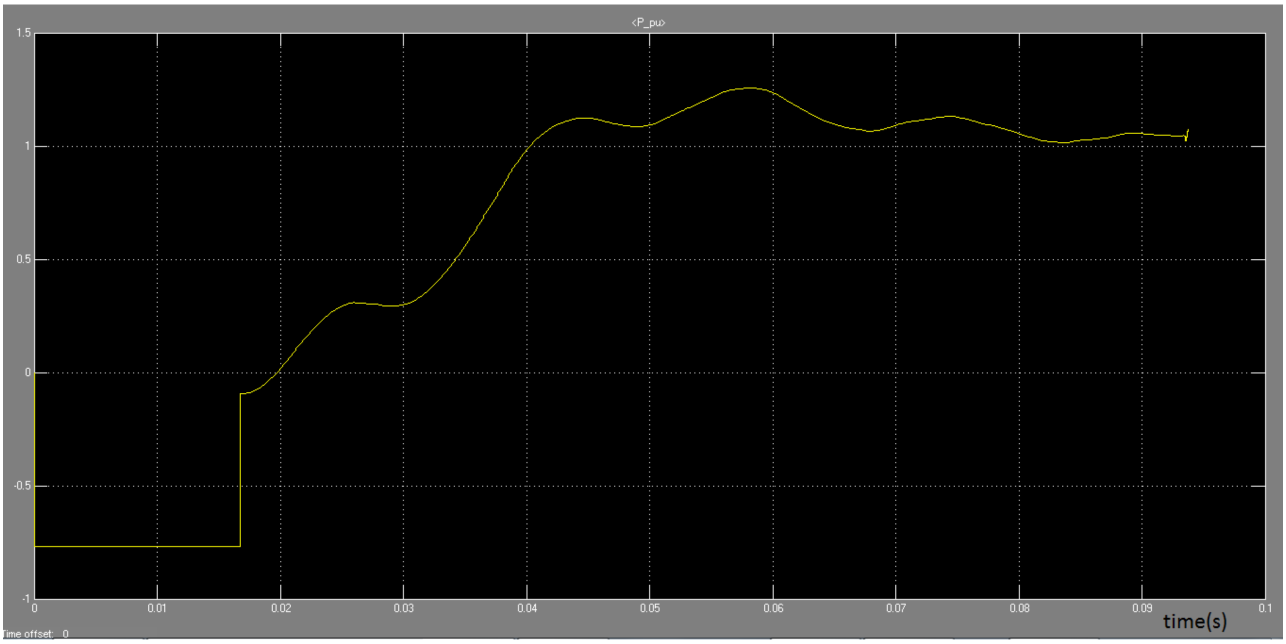


Fig: 5.8 Active Power

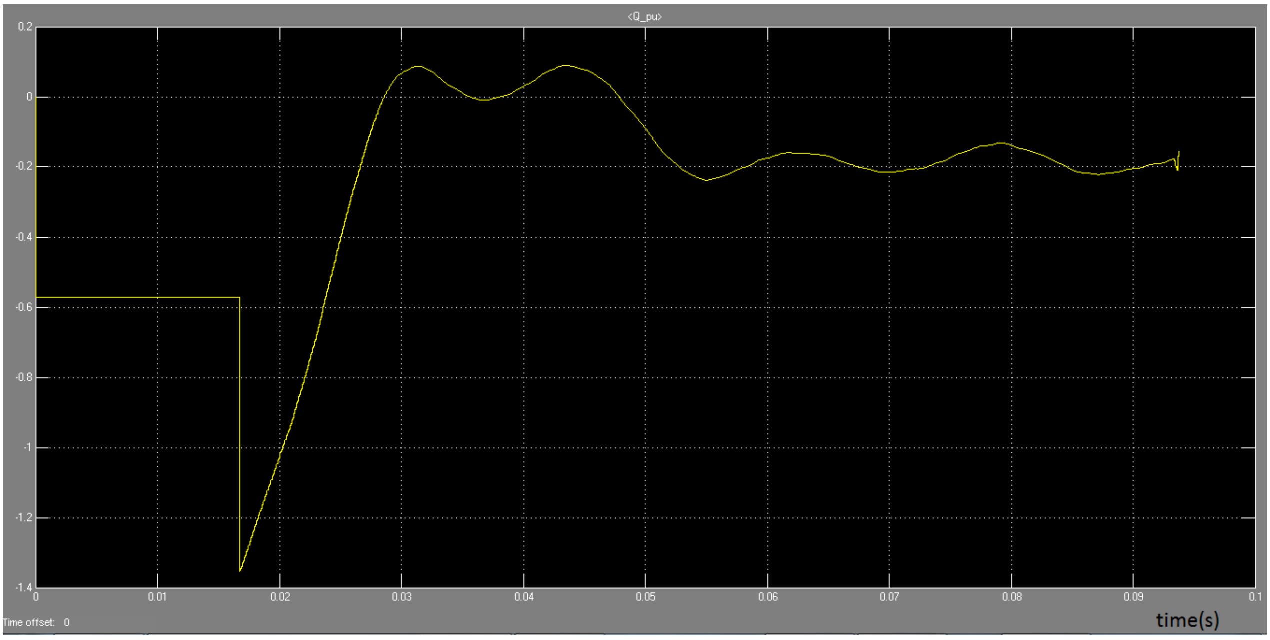


Fig: 5.9 Reactive Power

CONCLUSION:

DFIGs are enormously used in Wind farms because of their ability to supply power at constant voltage and frequency.Charactristics of DFIG are studied in MATLAB environment. Control techniques of DFIG have been analysed. Magnitude and Frequency control has been studied and a Simulink model for the same has been proposed. Unlike traditional methods like Stator flux orientation vector control and FMAC, the MFC method manipulates the magnitude and frequency of the rotor voltage. This simplifies the design of the control system and improves system reliability.

FUTURE WORK:

The parameters of the controllers can be improved or advanced control methods can be used in future to improve the stability and dynamic performance of grid connected induction generator.

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APPENDIX

DFIG RATING AND SPECIFICATION:

SPECIFICATION	**RATING**
RATED POWER	9MW
STATOR VOLTAGE	575V
STATOR RESISTANCE(R_s)	0.023Ω
ROTOR RESISTANCE(R_r)	0.016Ω
STATOR INDUCTANCE(L_s)	0.18H
ROTOR INDUCTANCE(L_r)	0.16H
MUTUAL INDUCTANCE(L_m)	2.9H
POLES	3
WIND SPEED AT NOMINAL SPEED AND AT C_P MAX	11 m/s
DC LINK VOLTAGE	1150V
DC BUS CAPACITOR	10000 µF
INERTIA CONSTANT	0.685